

Production of Forward Rapidity Photons in High Energy Heavy Ion Collisions

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Abstract

We consider production of prompt photons in high energy gold-gold and deuteron-gold collisions in the forward rapidity region of RHIC ($y \sim 3.8$). In this kinematics, the projectile partons typically have large x_{bj} while the target partons are mostly at very small x_{bj} so that the primary partonic collisions involve valence quarks from the projectile and gluons from the target. We take the target nucleus to be a Color Glass Condensate while the projectile deuteron or nucleus is treated as a dilute system of partons. We show that the photon production cross section can be written as a convolution of a quark-nucleus scattering cross section, involving a quark anti-quark dipole, with the Leading Order quark-photon fragmentation function. We consider different models of the quark anti-quark dipole and show that measurement of photons in the forward rapidity region at RHIC can distinguish between different parameterizations of the dipole cross section as well as help clarify the role of parton coalescence models in hadron production at RHIC.

1 Introduction

Recent observation of the suppression of produced hadron spectra in high energy deuteron-gold collisions in the forward rapidity region at RHIC has caused much excitement in the field [1]. While classical multiple scattering, appropriate for mid rapidity RHIC, give an enhancement of the p_t spectra in nuclear collisions [2] as compared to spectra in proton-proton collisions, the Color Glass Condensate formalism predicts a suppression of the p_t spectra in the forward rapidity region due to the small x evolution and high density of gluons in the target nucleus [3]. Recent calculations of hadron spectra in deuteron-gold collisions based on Color Glass Condensate formalism have been quite successful in describing the RHIC data [4]. More recently, some models based on parton coalescence have been used to fit the forward rapidity data [5]. While the success of these models does not necessarily contradict the Color Glass Condensate formalism (since these models use the low transverse momentum data to tune their parameters), it is imperative to measure other observable, such as dilepton and photons, in order to gain a better understanding of the degree to which the Color Glass Condensate is the dominant physics in the forward rapidity region and to what degree parton coalescence models are relevant. For instance, if photon production in the forward rapidity deuteron-gold collisions is suppressed analogously to hadron production, it would confirm gluon saturation as the correct physics for particle production with no need for parton coalescence. Electromagnetic probes such as dileptons and photons have the further advantage that they do not interact strongly after they are produced and are therefore relatively clean even though their production rates are lower [6].

In this brief note, we calculate the production cross section for photons in the forward rapidity region at RHIC. Starting with the production cross section for a quark and a photon [7], we integrate over the quark transverse momentum and show that this integration leads to a divergence which is identified as the collinear divergence present when a massless quark emits a photon. We show that this divergence can be isolated and rewritten as the Leading Order (LO) quark-photon fragmentation function [8] so that the overall cross section can be written as the convolution of a quark-nucleus scattering cross section [9] and the quark-photon fragmentation function. In order to evaluate this cross section, we use the two available parameterizations of the dipole-nucleus cross section and show that they lead to quite different predictions for the ratio of cross sections in deuteron-gold and gold-gold collisions (R_{dA} and R_{AA}). This difference is attributed to the different shapes of the dipole with respect to its size in the two parameterizations. We then discuss the advantages and disadvantages of the two parameterizations.

In the very forward kinematic region, one probes the large x partons in the projectile (deuteron or gold) while probing the very small x region in the target nucleus. Therefore, we use the Color Glass Condensate formalism [10, 11] to describe the target nucleus. On the other hand, since the projectile deuteron or nucleus is mainly probed at large x , it is treated as a collection of partons, in this case, quarks and anti-quarks. Furthermore, in the case of a deuteron we ignore the nuclear modifications of the deuteron wave function since it is a small effect while in the case of a gold projectile, we use the EKS98 parameterization

of nuclear (anti) shadowing [12].

2 The Scattering Cross Section

The scattering cross section for production of a massless quark with momentum q_t and a photon with momentum k_t was considered in [7] and the following expression was derived (where z is the fraction of the parent quark carried away by the photon)

$$\frac{d\sigma^{q(p) A \rightarrow q(q) \gamma(k) X}}{dz d^2b_t d^2k_t} = \frac{e^2}{(2\pi)^5} z [1 + (1 - z)^2] \frac{1}{k_t^2} \int d^2q_t \frac{(q_t + k_t)^2}{[zq_t - (1 - z)k_t]^2} \tilde{N}(x, k_t + q_t, b_t) \quad (1)$$

where $\tilde{N}(x, k_t, b_t)$ is the dipole cross section in the momentum space defined as

$$\tilde{N}(x, k_t, b_t) = \int d^2r_t e^{ik_t \cdot r_t} N(x, r_t, b_t) \quad (2)$$

and

$$N(x, r_t, b_t) = \frac{1}{N_c} Tr < 1 - V^\dagger(x_t) V(y_t) > \quad (3)$$

with $r_t \equiv x_t - y_t$ and $b_t \equiv (x_t + y_t)/2$. In order to obtain the photon production cross section, we integrate over the produced quark momentum q_t . As is clear from (1), there is a collinear singularity at $zq_t = (1 - z)k_t$. Shifting $zq_t \rightarrow zq_t + (1 - z)k_t$ leads to the following expression for the q_t dependent part of the expression (1), up to some finite pieces,

$$\int_0^{\hat{s}} \frac{d^2q_t}{q_t^2} e^{iq_t \cdot r_t} \quad (4)$$

which gives $\pi \log \hat{s}/\Lambda^2$ where \hat{s} is the subpartonic center of mass energy squared and Λ is an infrared cutoff. It is common to write this log as a sum of two pieces $\log \hat{s}/\Lambda^2 \equiv \log \hat{s}/Q^2 + \log Q^2/\Lambda^2$ where Q is the factorization scale. The collinear singularity is then absorbed in the quark-photon fragmentation function $D_{\gamma/q}(z, Q^2)$. The fragmentation function evolves with the factorization scale Q and obeys an evolution equation similar to DGLAP for the parton distribution functions. At the Leading Log level, this evolution does not change the Q^2 dependence but does change the z dependence. Since we are working in a limited transverse momentum range, the DGLAP evolution of the fragmentation function is not important and will be neglected. Furthermore, the fragmentation piece is the parametrically important one since it is formally of order $\frac{1}{\alpha_s}$ which cancels a factor of the strong coupling constant in the hard cross section so that it is more leading (in α_s) than the other piece which is sub-leading. Extracting the Leading Order quark-photon splitting function $P_{\gamma/q} \equiv \frac{e^2 e_q^2}{8\pi^2} \frac{1+(1-z)^2}{z}$ and identifying $D_{\gamma/q}(z, Q^2) \equiv P_{\gamma/q} \log Q^2/\Lambda^2$ as the Leading Order quark-photon fragmentation function, the cross section reduces to

$$\frac{d\sigma^{q A \rightarrow \gamma X}}{dz d^2b_t d^2k_t} = \frac{1}{(2\pi)^2} \frac{1}{z^2} D_{\gamma/q}(z, k_t) \tilde{N}(x, k_t/z, b_t) \quad (5)$$

where $z \equiv \frac{k_t}{x_q \sqrt{s}} e^{y_\gamma}$ and x_q is the fraction of the projectile hadron (nucleus) carried by the incoming quark and y_γ is the produced photon rapidity. To relate this to deuteron (nucleus)-nucleus scattering, we convolute the above with the quark (and anti-quark) distribution functions of the projectile deuteron or nucleus and sum over the different quark (anti-quark) flavors

$$\frac{d\sigma^{d(A) A \rightarrow \gamma(k_t, y_\gamma) X}}{d^2 b_t d^2 k_t dy_\gamma} = \frac{1}{(2\pi)^2} \sum_f \int dx_q [q_f(x_q, k_t^2) + \bar{q}_f(x_q, k_t^2)] \frac{D_{\gamma/q}(z, k_t^2)}{z} \tilde{N}(x_g, \frac{k_t}{z}, b_t) \quad (6)$$

where $x_g = \frac{k_t}{\sqrt{s}} e^{-y_\gamma}$ and the lower limit in the x_q integration is $x_q^{min} = \frac{k_t}{\sqrt{s}} e^{y_\gamma}$.

We use eq. (6) to calculate the photon production cross section in deuteron (gold)-gold collisions. In the case of deuteron-gold collisions, we will ignore nuclear modifications of the deuteron since they are small in this kinematic region. In the case of projectile gold nucleus, we use the parameterization of quark and anti-quark distribution functions due to Eskola et al. [12]. The main effect in the projectile nucleus wave function is anti-shadowing of quarks and anti-quarks which can be as big as 10% in the large x region where the projectile partons are. Furthermore, we will concentrate on central collisions since this is where the effects of Color Glass Condensate in nuclei is most prominent so that our results are meant for photon production in the most central collisions, for example, 0–5%. Generalizing this to more peripheral collisions is conceptually straightforward but requires a Monte Carlo simulation of centrality classes which is time consuming and numeric intensive. Since we are mostly interested in the effects of the Color Glass Condensate on the produced photon spectra, we will limit ourselves to the most central collisions and leave the impact parameter dependence of the spectra for a future study.

To proceed further, we need to know the dipole cross section $N(x_g, r_t, b_t)$. One can in principle solve the JIMWLK equations for N subject to some initial condition. This has not been accomplished so far since the JIMWLK equations are highly non-linear, coupled equations. Rather, the large N_c limit of JIMWLK equations (known as the BK equation [13]) has been studied in detail and approximate analytical solutions have been found in the high energy (large rapidity) limit [14]. Alternatively, phenomenological models of the dipole cross section, which respect the general properties of the JIMWLK equations) have been proposed and used to fit the data from HERA and RHIC. In this work, we use the two known parameterizations of the dipole cross section proposed in [15] and [16]. We show that the two models lead to rather different predictions for the dependence of the nuclear modification factors R_{dA} and R_{AA} with the photon momentum k_t so that, in principle, measurement of the nuclear modification factor in deuteron (gold)-gold collisions in the forward rapidity region at RHIC can shed further light on the detailed dynamics of the Color Glass Condensate.

In Fig. (1), we show the dipole profile for a proton using the two parameterizations, due to Iancu et al. [15] (denoted IIM) and due to Kharzeev et al. [16] (denoted KKT) for $x_g = 1.6 \times 10^{-4}$ ($k_t = 1.5$ GeV at $y_{photon} = 3.8$) in terms of the dimensionless parameter $r_t Q_s$. Clearly, the two models lead to quite different results. In Fig. (2), we show the dipole profile for a gold target for the same values of x_g . Again, the two parameterization

are quite different. The profiles shown are for one specific value of x_g on which the profile depends quite sensitively. In evaluating the production cross section, one samples different values of x_g where the dipole profiles are different. Nevertheless, the above figures illustrate the difference in the available parameterizations of the dipole profile which leads to different predictions for the nuclear modification factors.

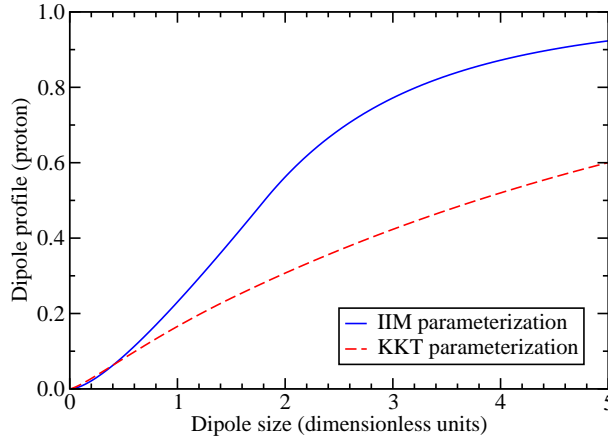


Figure 1: Quark anti-quark dipole profile for a proton target.

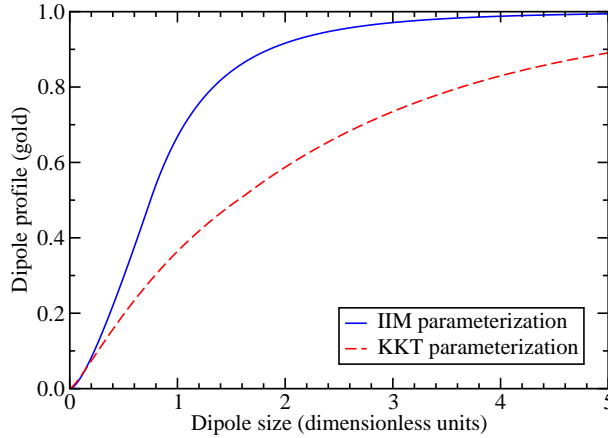


Figure 2: Quark anti-quark dipole profile for a nuclear target.

We now use the two parameterizations of the dipole cross section in coordinate space and Fourier transform them to momentum space and use the result in (6) to get the photon production cross section in deuteron-gold and gold-gold collisions. As discussed above, we limit ourselves to central collisions and forward rapidity. Since the STAR experiment at RHIC has the capability to measure photons at $y = 3.8$, we evaluate the nuclear modification factor for this rapidity. The nuclear modifications factors R_{dA} and R_{AA} are defined

as

$$R_{dA} \equiv \frac{\frac{d\sigma^{dA \rightarrow \gamma X}}{dy d^2k_t d^2b_t}}{2A \frac{d\sigma^{pp \rightarrow \gamma X}}{dy d^2k_t d^2b_t}} \quad \text{and} \quad R_{AA} \equiv \frac{\frac{d\sigma^{AA \rightarrow \gamma X}}{dy d^2k_t d^2b_t}}{A \frac{d\sigma^{pp \rightarrow \gamma X}}{dy d^2k_t d^2b_t}}. \quad (7)$$

The A dependence of our normalization of R_{AA} may look different from the commonly used one. However, this is due to our use of EKS shadowing of projectile quark and anti-quark distributions which are normalized to unity in the absence of nuclear effects and because of the impact parameter slice d^2b_t which is different for a proton and a nucleus.

We show our results for the nuclear modification factors R_{dA} and R_{AA} in Figs. (3) and (4). The dependence of the modification factor on the photon transverse momentum is quite different for the two dipole parameterizations due to the different dipole profiles. The IIM dipole parameterization has a sharper dependence on its size unlike the KKT parameterization which grows slower. This is mainly responsible for the sharp rise of the cross section with k_t in the IIM parameterization. Another difference between the two parameterization is that the IIM dipole parameterization does not have the correct high k_t behavior in the double log region unlike the KKT parameterization which has the right high k_t dependence built in.

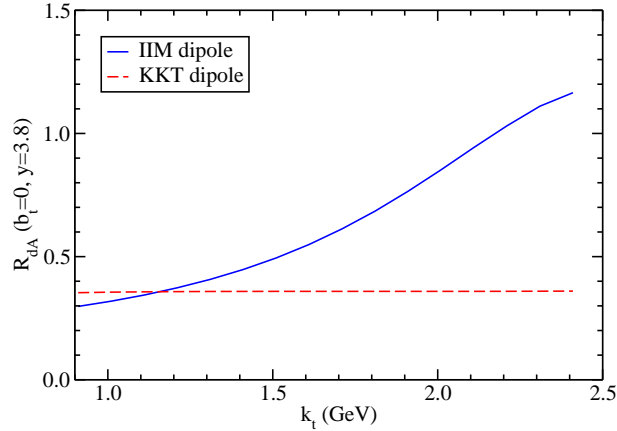


Figure 3: Nuclear modification factor for photon production in deuteron-gold collisions.

Furthermore, the quark and anti-quark distributions in the projectile deuteron and gold are somewhat different due to the anti-shadowing present in the gold nucleus in the large x region. This causes the gold nuclear modification factor R_{AA} to be larger than the deuteron nuclear modification factor R_{dA} .

3 Discussion

Measurement of the nuclear modifications factors for photon production in the forward rapidity region in deuteron-gold and gold-gold collisions can help illuminate the presence

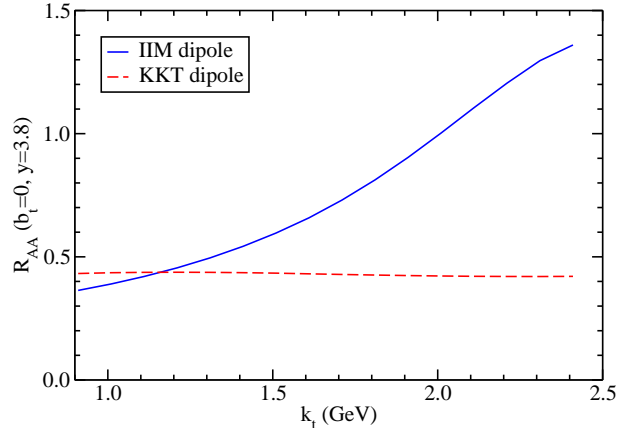


Figure 4: Nuclear modification factor for photon production in gold-gold collisions.

of the Color Glass Condensate and shed further light on the detailed dynamics of gluon saturation. The forward rapidity region is unique in the sense that one probes the smallest kinematically allowed x in the target and that final state effects are expected to be negligible, unlike mid rapidity gold-gold collisions where final state effects such as the Quark Gluon Plasma are the dominant effects at RHIC.

The two available parameterizations of the dipole cross section, which is the common element in both hadron and photon production in the forward rapidity region¹, have distinctly different transverse momentum dependences which can be used to further constrain these models. Both IIM and KKT parameterizations have advantages as well as disadvantages. The main advantage of IIM and KKT parameterizations of the dipole profile, as compared to for instance, the Golec-Biernat-Wusthoff parameterization [19], is that these two models have the correct anomalous dimension in the low density region which seems to be crucial for understanding the observed suppression of the forward rapidity data on hadron production at RHIC. The IIM parameterization of the dipole cross section has been made to fit the DIS data on proton targets in HERA and has not been used for nuclear targets. Our simple procedure to use it for nuclei by scaling it by a presumed $A^{1/3}$ dependence may be too naive since it is not clear that this is valid for all dipole sizes. There is a recent study of nuclear DIS data which claims a $A^{2/3}$ dependence [20]. However, the nuclear data are very limited in the small x region and the error bars are large. Furthermore, the DIS structure functions involve a convolution of the dipole cross section with the virtual photon wave function squared which weighs different dipole sizes differently. The KKT parameterization, on the other hand, is a fit to particle production data at RHIC and has not been checked against DIS data on proton targets at HERA. Nevertheless, particle production cross section is a less inclusive quantity than a structure function measured in DIS and is therefore more constraining even though the presence of a convolution with

¹Note that two particle production cross section involves higher point correlation functions of Wilson loops [17, 18] unlike single particle production which involves only the two point function of (fundamental or adjoint) Wilson lines.

the hadron fragmentation function makes things more non-trivial. Clearly, one needs to check these parameterizations of the dipole profile in different observables, such as photon production considered in this work.

Measuring low k_t photons in the forward rapidity kinematics will be challenging. One will need to understand the photon background, due mainly to photons coming from neutral pion and η meson decays. At the moment, pions are well measured at RHIC and one can accurately take their contributions into account. The same is true for η mesons with somewhat less accuracy. The present data from the last gold-gold run at RHIC should be precise enough to measure the R_{AA} while another deuteron-gold may be necessary to get enough statistics in order to extract R_{dA} precisely. Another source of photons in the forward rapidity region is the direct production which become larger than the fragmentation photons in the high k_t region. In order to estimate the relative contribution of direct photons, we note that in forward proton-proton collisions at RHIC, direct photons contribute about 10 – 15% at $k_t = 1$ GeV while at $k_t = 4$ GeV their contribution is equal to the contribution from the fragmentation photons. A precise measurement of the very forward rapidity photons at low k_t will go a long way toward establishing the Color Glass Condensate as the dominant physics in the forward rapidity region at RHIC.

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